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Simulation of Respiratory Mechanics

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Contents

1 Introduction

The human respiratory system is a highly dynamic and complex system, responsible for oxygen intake and carbon dioxide removal. Its mechanical performance can be significantly impacted by diseases such as restrictive and obstructive pulmonary disorders. Understanding how these pathologies affect ventilation is essential biomedical engineering applications.

In this study, we used a MATLAB-Simulink-based simulator developed by David Leonardo Rodriguez Sarmiento and Daniela Acevedo Guerrero (2020), titled *Simulation of Respiratory Mechanics on Simulink with GUI*, to model and analyze respiratory behavior under three different conditions: healthy, restrictive, and obstructive.

2 Methodology

Simulator Details

- **Tool:** Simulink GUI from MATLAB File Exchange
- **Access URL:** https://www.mathworks.com/matlabcentral/fileexchange/75335

Ventilator Settings

The following ventilator parameters were kept constant across all simulation scenarios:

Parameter	**Value**
Breaths Per Minute (BPM)	15
Peak Pressure	10 cmH_2O
Inspiratory:Expiratory Ratio (I:E)	1:1
Positive End-Expiratory Pressure (PEEP)	0 cmH_2O

Table 1: Fixed ventilator settings used for all conditions

Physiological Parameters Adjusted

Each simulation scenario involved varying key parameters to reflect the physiological characteristics of healthy or diseased lungs:

- **Lung Compliance :** Ability of the lungs to expand.
- **Thoracic Compliance :** Compliance of the chest wall.
- **Central Airway Resistance :** Resistance in large airways.
- **Peripheral Airway Resistance :** Resistance in smaller airways.
- **Airway Tissue Compliance :** Elasticity of airway tissues.

3 Simulation Scenarios and Results

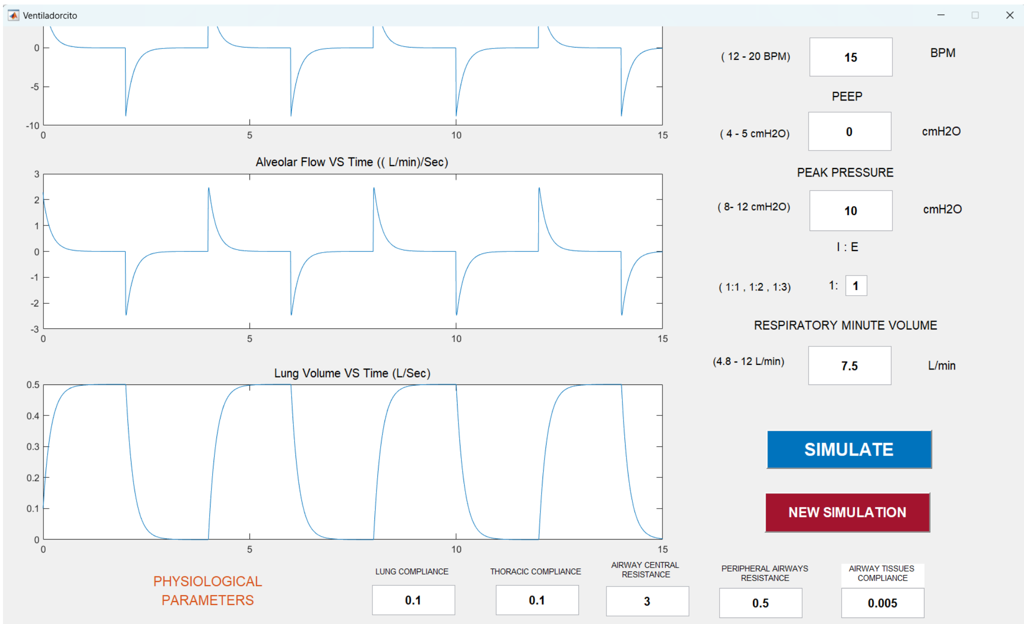
3.1 Normal Lung Function

This scenario simulates healthy pulmonary mechanics. Lung and thoracic compliance are within standard ranges, and airway resistances are low, ensuring efficient ventilation.

- Lung Compliance: 0.1 L/cmH_2O
- Thoracic Compliance: 0.1 L/cmH_2O
- Central Resistance: 3 cmH_2O·s/L
- Peripheral Resistance: 0.5 cmH_2O·s/L
- Tissue Compliance: 0.005 L/cmH_2O

Results:

- Minute Ventilation: 7.5 L/min
- Peak Transpulmonary Pressure: 8 cmH_2O
- Peak Alveolar Flow: 2.5 L/min
- Peak Lung Volume: 0.5 L



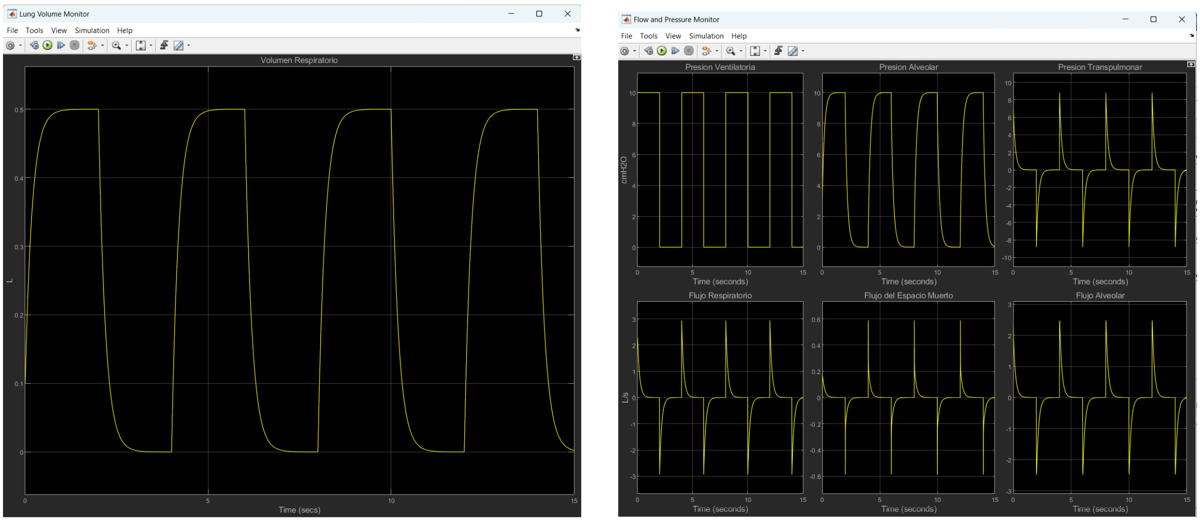


Figure 1: Ventilation performance under normal lung function

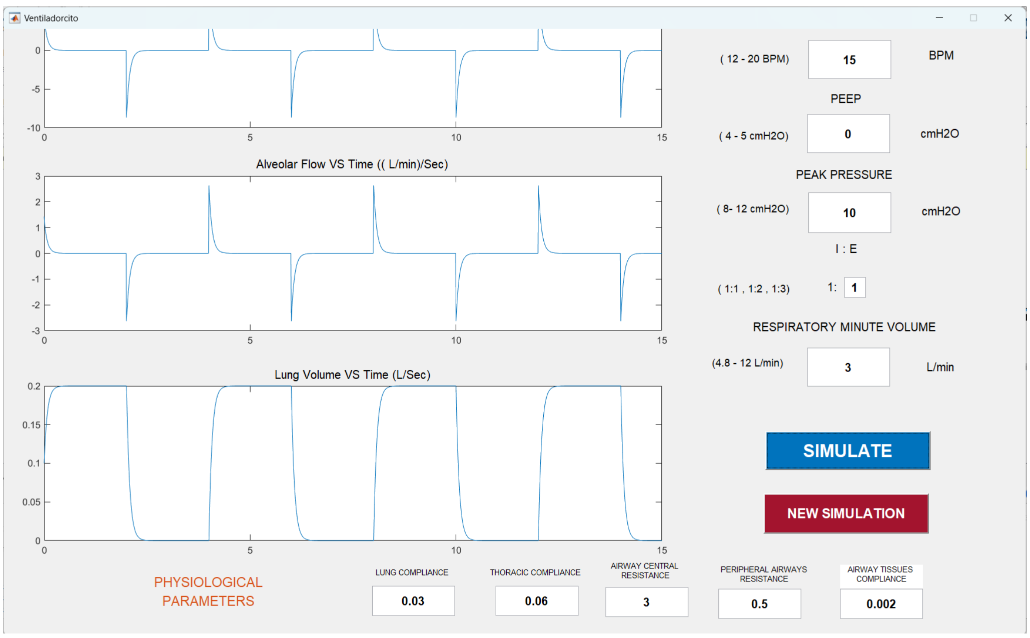
3.2 Restrictive Condition (e.g., Pulmonary Fibrosis)

Restrictive lung diseases are characterized by a significant reduction in lung compliance, making the lungs stiff and difficult to expand. In this simulation, decreased lung and thoracic compliance results in a reduced tidal volume and consequently lower minute ventilation.

- Lung Compliance: 0.03 L/cmH_2O
- Thoracic Compliance: 0.06 L/cmH_2O
- Central Resistance: 3 cmH_2O·s/L
- Peripheral Resistance: 0.5 cmH_2O·s/L
- Tissue Compliance: 0.002 L/cmH_2O

Results:

- Minute Ventilation: 3 L/min
- Peak Lung Volume: 0.2 L
- Reduced minute ventilation and lung volume.
- Flow waveform: Narrow and sharp due to reduced expansion.



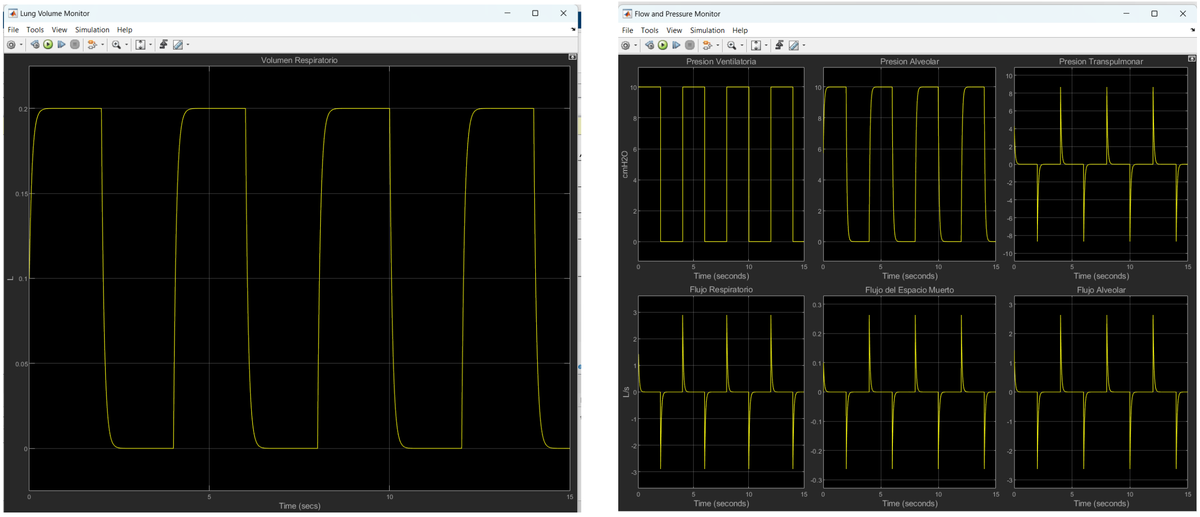


Figure 2: Ventilation graphs under restrictive lung disease

By changing the ventilator settings as below we can aid a person with restrictive lung disease.

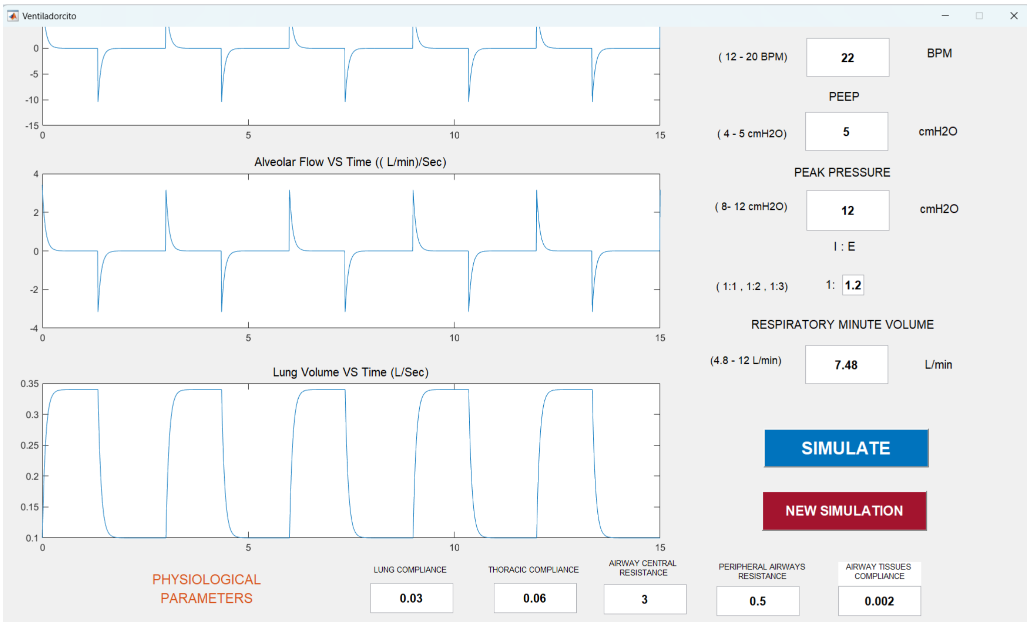


Figure 3: Changing the ventilator settings to mitigate the condition

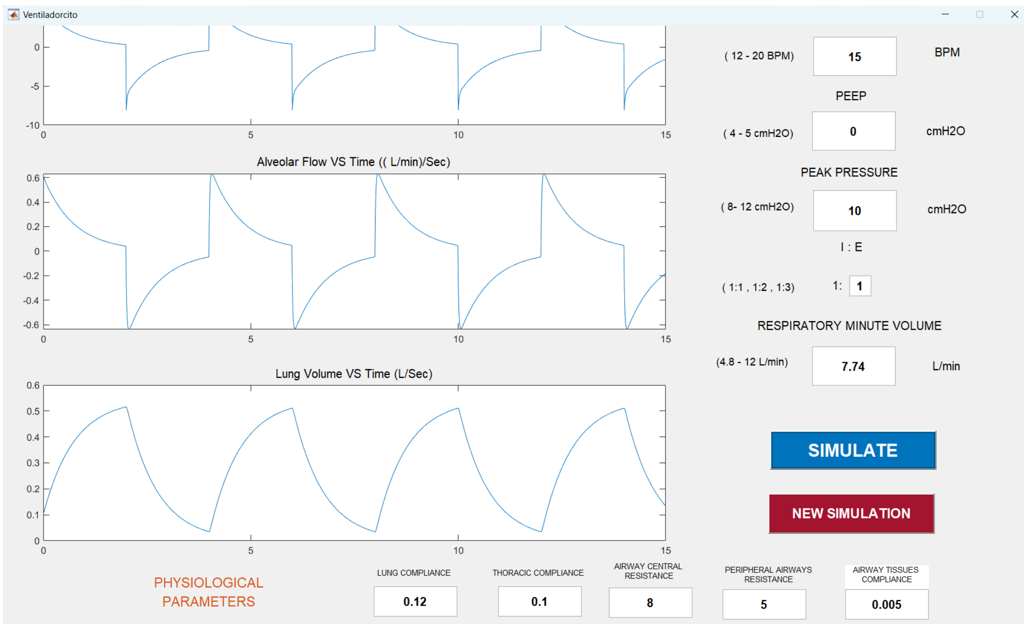
3.3 Obstructive Condition (e.g., COPD)

Obstructive diseases like COPD mainly affect airway resistance, particularly in the peripheral bronchioles. Although lung compliance remains normal or even slightly elevated, airflow obstruction during exhalation leads to air trapping, reduced expiratory flow, and dynamic hyperinflation.

- Lung Compliance: 0.12 L/cmH_2O
- Thoracic Compliance: 0.1 L/cmH_2O
- Central Resistance: 8 cmH_2O·s/L
- Peripheral Resistance: 5 cmH_2O·s/L
- Tissue Compliance: 0.005 L/cmH_2O

Results:

- Expiratory phase was prolonged due to elevated resistance.
- Signs of dynamic hyperinflation(air trapping) as the transpulmonary pressure doesn't return to the base line at the end of exhalation.
- Alveolar flow has reduced to 0.6 L/sec.
- Although minute ventilation may appear adequate, gas exchange is compromised.



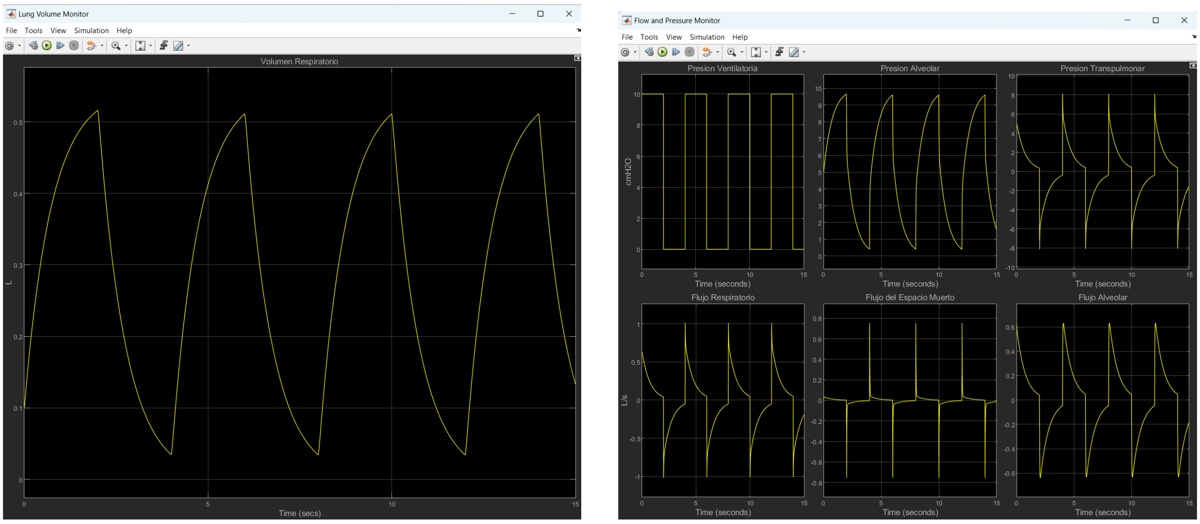


Figure 4: Ventilation graphs under obstructive lung disease

4 Comparison of Minute Ventilation

- **Normal lungs:** Compliance and resistance are within physiological range. Tidal volume is adequate, resulting in normal minute ventilation (7.5 L/min).

- **Restrictive lung disease:** Decreased lung compliance limits lung expansion, drastically reducing tidal volume. As a result, minute ventilation drops to 3 L/min, even if respiratory rate remains the same.

- **Obstructive lung disease:** Increased airway resistance leads to air trapping. Although minute ventilation may appear normal at 7.74 L/min, effective alveolar ventilation is reduced.

  A key takeaway is that minute ventilation alone can be misleading when assessing respiratory function. Although both the normal and obstructive conditions show similar minute ventilation values (7.5 L/min and 7.74 L/min respectively), the efficiency of gas exchange differs significantly due to air trapping in obstructive disease. Meanwhile, restrictive disease shows a clear drop in minute ventilation (3 L/min), primarily due to reduced tidal volume from decreased lung compliance.

5 Conclusion

This simulation highlights how pulmonary compliance and airway resistance distinctly affect breathing mechanics across different respiratory pathologies.

- **Normal lungs:** Lung compliance and airway resistance are within the physiological range. This ensures effective lung expansion and unimpeded airflow. The tidal volume remains normal, supporting a healthy minute ventilation of 7.5 L/min, which enables efficient gas exchange.

- **Restrictive lung disease:** A significant reduction in lung compliance prevents full lung expansion. Despite maintaining the same respiratory rate, the tidal volume is drastically reduced, leading to a marked drop in minute ventilation to just 3 L/min. This reduction compromises oxygen uptake and carbon dioxide elimination.

- **Obstructive lung disease:** Although lung compliance may be preserved or increased, there is substantial elevation in airway resistance—especially in smaller peripheral airways. This impairs airflow, particularly during expiration, resulting in air trapping and an increase in residual volume. While minute ventilation appears almost normal (7.74 L/min), the actual alveolar ventilation is significantly reduced, as part of the ventilated air does not participate effectively in gas exchange.